Hidden Source of High-Energy Neutrinos in Collapsing Galactic Nucleus

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Abstract

We propose a model of a short-lived extremely powerful source of high energy neutrinos. It is formed as a result of dynamical evolution of a galactic nucleus prior to its collapse into the massive black hole. A dense central stellar cluster in the galactic nucleus on the late stage of evolution consists of compact stars (neutron stars and stellar mass black holes). This cluster is sinked deep into the massive gas envelope produced in the collisions of the primary stellar population. The frequent collisions of remaining neutron stars in central stellar cluster result in a creation of ultrarelativistic fireballs and shock waves. They produce the rarefied cavern with external shell and quasi-stationary external shock. The particles are effectively accelerated in the cavern and, due to pp-collisions in the gas envelope, they produce high energy neutrinos. All high energy particles, except neutrinos, are absorbed in the thick envelope. Duration of active stage is ~ 10 yr, the number of the sources can be ~ 10 per cosmological horizon. High energy neutrino signal can be detected by underground neutrino telescope with effective area $S \sim 1$ km^2.

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1 Introduction: Hidden Sources

High energy (HE) neutrino radiation from astrophysical sources is accompanied by other radiations most notably by HE gamma radiation. These radiations can be used to put upper limit on the neutrino flux emitted from a source. For example, if neutrinos are produced due to interaction of HE protons with low energy photons in extragalactic space or in the sources transparent for gamma radiation, the upper limit on diffuse neutrino flux $I_\nu(E)$ can be derived from e-m cascade radiation. This radiation is produced due to collisions with photons of microwave radiation γ_{bb}, such as $\gamma + \gamma_{bb} \rightarrow e^+ + e^-, \quad e + \gamma_{bb} \rightarrow e' + \gamma'$ etc. These cascade processes transfer the energy density released in high energy photons ω_γ into energy density of the remnant cascade photons ω_{cas}. These photons get into observed energy range 100 MeV$-$10 GeV and their energy density is limited by recent EGRET observations [1] as $\omega_{cas} \leq 2 \cdot 10^{-6}$ eV/cm^3. Introducing the energy density for neutrinos with individual energies higher than E, $\omega_\nu(> E)$, it is easy to obtain the following chain of inequalities (reading from left to write)

$$\omega_{cas} > \omega_\nu(> E) = \frac{4\pi}{c}\int_E^\infty EI_\nu(E)dE > \frac{4\pi}{c}E\int_E^\infty I_\nu(E)dE = \frac{4\pi}{c}EI_\nu(> E). \tag{1}$$

Now the upper limit on the integral HE neutrino flux can be written down as

$$I_\nu(> E) < \frac{4\pi}{c}\frac{\omega_{cas}}{E} = 4.8 \cdot 10^3 E_{eV}^{-1}\ cm^{-2}s^{-1}sr^{-1} \tag{2}$$

However, there can be sources, where accompanying radiations, such as gamma and X-rays, are absorbed. They are called "hidden sources" [2]. Several models of hidden sources were discussed in the literature.

- *Young SN shells* [3] during time $t_\nu \sim 10^3 - 10^4$ s are opaque for all radiations, but neutrinos.
- *The Thorn-Zytkow star* [4], the binary with a pulsar submerged into a red giant, can emit HE neutrinos while all kinds of e-m radiation are absorbed by the red giant component.
- *Cocooned massive black hole* (MBH) in AGN [5] is an example of AGN as hidden source: e-m radiations are absorbed in a cocoon around the massive black hole.
- *AGN with a standing shock* in vicinity of the MBH [6] can produce large flux of HE neutrinos with relatively weak X-ray radiation.

In this paper we propose a new model of a hidden source which can operate in galactic nucleus on the stage prior of MBH formation. We consider a near collapsing central cluster of compact stars in the galactic nucleus. Collisions of these stars result in formation of a rarefied cavern filled by the fireballs and shocks. Particles accelerated in this cavern interact with the gas in the surrounding gas envelope, producing the flux of HE neutrinos. Accompanying gamma radiation can be fully absorbed in the case of thick envelope (matter depth $X_{env} \sim 10^4$ g/cm^2). The proposed source is short-lived (life duration $t_s \sim 10$ years) and extremely powerful: neutrino luminosity exceeds the Eddington limit.

2 The Model

We consider in the following the basic features of the formation of the short-lived extremely powerful hidden source of HE neutrinos in the dynamically evolving central stellar cluster of typical galactic nucleus.

2.1 Dynamical Evolution of Galactic Nucleus

The dynamical evolution of dense central stellar clusters in the galactic nuclei is accompanied by the secular growth of the velocity dispersion of constituent stars v or, equivalently, by the growth of the central gravitational potential. This process is terminated by the formation of the MBH when the velocity dispersion of the stars grows up to the light speed (see for a review e.g. [7] and references therein). On its way to the MBH formation the dense galactic nuclei inevitably proceed through the stellar collision phase of evolution [8] - citedok91. when all normal stars in the cluster are disrupted in mutual collisions of fast-moving constituent stars. The necessary condition for the collisional destruction of normal stars with mass m_* and radius r_* in the cluster of identical stars with a velocity dispersion v is $v > v_p$, where

$$v_p = \left(\frac{2Gm_*}{r_*}\right)^{1/2} \simeq 6.2 \cdot 10^2 \left(\frac{m_*}{\mathrm{M}_\odot}\right)^{1/2} \left(\frac{r_*}{R_\odot}\right)^{-1/2} \ \mathrm{km\ s}^{-1}. \tag{3}$$

is an escape (parabolic) velocity from the surface of a constituent normal star. Under this inequality the kinetic energy of colliding star is greater in general than its gravitational bound energy. If $v > v_p$ the normal stars are eventually disrupted in mutual collisions or in collisions with the extremely compact stellar remnants: neutron stars (NSs) or stellar mass black holes (BHs). Only these compact stellar remnants survive through the stellar-destruction phase of evolution ($v = v_p$) and form the self-gravitating core. We shall refer to this core as to the NS cluster. Meanwhile the remnants of disrupted normal stars form a gravitationally bound massive gas envelope in which the NS cluster is submerged. A virial radius of this envelope is

$$R_{env} = \frac{GM_{env}}{2v_p^2} = \frac{1}{4}\frac{M_{env}}{m_*}r_* \simeq 0.56 M_8 \left(\frac{m_*}{\mathrm{M}_\odot}\right)^{-1}\left(\frac{r_*}{R_\odot}\right) \ \mathrm{pc}, \tag{4}$$

where $M_{env} = 10^8 M_8 \mathrm{M}_\odot$ is a corresponding mass of the envelope. The gas from disrupted normal stars composes the major part of the progenitor central stellar cluster in the galactic nucleus. So the natural range for the total mass of the envelope is the same as the typical range for the mass of a central stellar cluster in the galactic nucleus, $M_{env} = 10^7 - 10^8 \mathrm{M}_\odot$. A radius of the envelope R_{env} is fixed by the virial radius of the central cluster of the galactic nucleus at the moment of evolution when $v = v_p$. The envelope is expected to be inhomogeneous and clumpy, and it is supported in a virial equilibrium by the kinetic motion of the constituent gas clouds, driven by activity of the inner NS cluster (see below). Thus, the envelope is similar in structure to the broad line region around the central source of radiation in AGN. Only averaged parameters of the envelope are essential for the considered model. The mean number density of gas in the envelope is

$$n_{env} = \frac{3}{4\pi}\frac{1}{R_{env}^3}\frac{M_{env}}{m_p} \simeq 5.4 \cdot 10^9 M_8^{-2}\left(\frac{m_*}{\mathrm{M}_\odot}\right)^{3}\left(\frac{r_*}{R_\odot}\right)^{-3} \ \mathrm{cm}^{-3}, \tag{5}$$

where m_p is a proton mass. The column density of the envelope is

$$X_{env} = m_p n_{env} R_{env} \simeq 1.6 \cdot 10^4 M_8^{-1}\left(\frac{m_*}{\mathrm{M}_\odot}\right)^{2}\left(\frac{r_*}{R_\odot}\right)^{-2} \ \mathrm{g\ cm}^{-2}. \tag{6}$$

Such an envelope completely absorbs electromagnetic radiations and HE particles outgoing from the interior, except neutrinos and gravitational waves.

2.2 Dense Cluster of Stellar Remnants

As was discussed above, the dense NS cluster survives inside the massive envelope of the post-stellar-destruction galactic nucleus. The total mass of this cluster is $\sim 1-10$ % of the total mass of a progenitor galactic nucleus [8] - [11] and so of the massive envelope, i. e. $M \sim 0.01 - 0.1 M_{env}$. We will use the term 'evolved galactic nucleus' for this cluster of NSs assuming that (i) $v > v_p$ and (ii) the (two-body) relaxation time in the cluster is much less than the age of the host galaxy. Under the last condition the cluster has enough time for an essential dynamical evolution. For example the relaxation time of stars inside the central parsec of the Milky Way galaxy is $t_r \sim 10^7 - 10^8$ years. The further dynamical evolution of the evolved cluster is terminated by the formation of the MBH.

We consider in the following an evolved central cluster of NSs with identical masses $m = 1.4 \mathrm{M}_\odot$. This evolved cluster of NSs is sinked deep inside of a massive gas envelope remaining after the previous evolution epoch of a typical normal galactic nucleus. Let $N = M/m = 10^6 N_6$ is a total number of NSs stars in the cluster. The virial radius of this cluster is:

$$R = \frac{GNm}{2v^2} = \frac{1}{4}\left(\frac{c}{v}\right)^2 N r_g \simeq 1.0 \cdot 10^{13} N_6 (v/0.1c)^{-2} \text{ cm}, \tag{7}$$

where $r_g = 2Gm/c^2$ is a gravitational radius of NS. For $N \sim 10^6$ and $v \sim 0.1c$ one has nearly collapsing cluster with the virial size of $\sim$1 AU. The characteristic times are (i) the dynamical time $t_{dyn} = R/v = (1/4)N(c/v)^3 r_g/c \simeq 0.95 N_6 (v/0.1c)^{-3}$ hour and (ii) the evolution (two-body relaxation) time of the NS cluster $t_{rel} \simeq 0.1(N/\ln N) t_{dyn} \simeq 19 N_6^2 (v/0.1c)^{-3}$ years. In general $t_{rel} \gg t_{dyn}$, if $N \gg 1$. This evolution time determines the duration of an active phase for the considered below hidden source, as $t_s \sim t_{rel} \sim 10$ years.

2.3 Fireballs in Cluster

The most important feature of our model is a secular growing rate of accidental NS collisions in the evolving cluster, accompanied by a tremendous energy release. The corresponding rate of NS collisions in the cluster (with the gravitational radiation losses taken into account) is [13–15]

$$\begin{aligned} \dot{N} &= 9\sqrt{2}\left(\frac{v}{c}\right)^{17/7} \frac{c}{R} = 36\sqrt{2}\left(\frac{v}{c}\right)^{31/7} \frac{1}{N}\frac{c}{r_g} \\ &\simeq 4.4 \cdot 10^3 N_6^{-1} (v/0.1c)^{31/7} \text{ yr}^{-1}. \end{aligned} \tag{8}$$

The time between two successive NS collisions is

$$t_c = \dot{N}_c^{-1} = \frac{1}{9\sqrt{2}}\left(\frac{c}{v}\right)^{10/7} t_{dyn} = \frac{1}{36\sqrt{2}}\left(\frac{c}{v}\right)^{31/7} N \frac{r_g}{c}$$

$$\simeq \quad 7.3 \cdot 10^3 N_6 (v/0.1c)^{-31/7} \text{ s.} \tag{9}$$

Each NS collision produces an ultrarelativistic photon-lepton fireball [16–20], which we suppose are roughly spherically symmetric. The physics of fireballs is extensively elaborated especially in recent years for the modelling of cosmological gamma-ray bursts (GRBs) (for review see e. g. [21] and references therein). A newborn fireball expands with relativistic velocity, corresponding to the Lorentz factor $\Gamma_f \gg 1$. The other two relevant parameters of a fireball are total energy $E_0 = 10^{52} E_{52}$ ergs and the total baryonic mass

$$M_0 = E_0/\eta c^2 \simeq 5.6 \cdot 10^{-6} E_{52} \eta_3^{-1} M_\odot, \tag{10}$$

where baryon-loading mass parameter $\eta = 10^3 \eta_3$. The maximum possible Lorentz factor of expanding fireball is $\Gamma_f = \eta + 1$ during the matter-dominated phase of fireball expansion [16, 19]. During the initial phase of expansion, starting from the radius of the 'inner engine' $R_0 \sim 10^6 - 10^7$ cm, the fireball Lorentz factor increases as $\Gamma \propto r$, until it is saturated at the maximum value $\Gamma_f = \eta \gg 1$ at the radius $R_\eta = R_0 \eta$ (see e. g. [21]). Internal shocks will take place around $R_{sh} = R_0 \eta^2$, if the fireball is inhomogeneous and the velocity is not a monotonic function of radius, e.g. due to the considerable emission fluctuations of the inner engine [22–24]. The fireball expands with a constant Lorentz factor $\Gamma = \eta$ at $R > R_\eta$ until it snow-ploughed the mass M_0/η of ambient gas and looses half of its initial momentum. At this moment ($R = R_\gamma$) the deceleration stage starts [20, 25, 26].

Interaction of a fireball with a surrounding interstellar medium (ISM) determines the length of its relativistic expansion. In our case the fireball propagates through a massive envelope with a mean gas number density $n_{env} = \rho_{env}/m_p = n_9 10^9$ cm^{-3} as it follows from Eq. (5). Fireball propagates relativistically with $\Gamma \gg 1$ up to the distance determined by the Sedov length

$$l_S = \left(\frac{3}{4\pi} \frac{E_0}{\rho_{env} c^2} \right)^{1/3} \simeq 1.2 \cdot 10^{15} n_9^{-1/3} E_{52}^{1/3} \text{ cm.} \tag{11}$$

Fireball becomes mildly relativistic at radius $r = l_S$ due to sweeping up the gas from the ISM with the mass $M_0 \eta$. The radius $r = l_S$ is the end point of the ultrarelativistic fireball expansion phase. Far beyond the Sedov length radius ($r \gg l_S$) there is a non-relativistic Newtonian shock driven by a decelerated fireball. Its radius $R(t)$ obeys the Sedov–Taylor self-similar solution [27], with $R(t) = (E_0 t^2/\rho_{env})^{1/5}$. The corresponding shock expansion velocity is $u = (2/5)[l_S/R(t)]^{3/2} c \ll c$.

2.4 Cavern

We show here that relativistic fireballs in the dense central cluster of NSs produce the dynamically supported rarefied cavern deep inside the massive gaseous envelope. The cavern radius coincides with the Sedov length from Eq. (11). The distance between freely expanding successive fireballs according to Eq. (9) is

$$R_c = ct_c \simeq 2.2 \cdot 10^{14} N_6 (v/0.1c)^{-31/7} \text{ cm}. \tag{12}$$

Each new fireball expands in the nonstationary inter-fireball medium (IFM) created by the preceding fireballs if $R_c < l_S$. This condition according to Eqs. (8) and (11) is realized in the case of sufficiently frequent NS collisions or correspondingly at

$$v > v_c = \left[\frac{1}{36\sqrt{2}}\left(\frac{r_g}{l_S}\right)N\right]^{7/31} \simeq 6.9 \cdot 10^{-2} N_6^{7/31} E_{52}^{-7/93} n_9^{7/93} c. \tag{13}$$

The repeating fireballs will support dynamically the boundary between the cavern and dense massive envelope in a quasi-stationary state if repeating time of fireball generation t_c is less than the contraction time l_S/v_s, where the effective virial or 'sound' speed of gas in the envelope $v_s \sim v_p$ and v_p is given by Eq. (3). The condition $t_c < l_S/v_p$ can be rewritten as inequality $v > v_c(v_s/c)^{7/31}$. This generally is equivalent to one given by Eq. (13), due to a weak dependence on v_s. So we will use for simplicity the inequality from Eq. (13), i. e. condition $R_c < l_S$ as one for the existence of cavern.

The propagation of fireballs through a nonuniform IFM created by previous fireballs is a specific feature of our model in contrast to the 'standard' picture of a single GRB fireball expansion through almost homogeneous ISM in normal galaxy. The radii of the preceding and subsequent fireballs are $R_f(t) = ct$ and $c(t + t_c)$ respectively, where the time between the NS collisions t_c is determined by Eq. (9). We are interesting by the case $R_c \ll l_S$, when each successive fireball expands inside the preceding one. The corresponding density of the IFM created by the preceding fireball in the region $R_f(t) < l_S$ is

$$\rho_{IFM}(t) = \frac{3}{4\pi}\frac{M_0}{[c(t + t_c)]^3}, \tag{14}$$

where M_0 is a fireball mass from Eq. (10). Each subsequent fireball sweeps away a mass $M_{sw}(t)$ from the IFM produced by the preceding one which grows with time as

$$M_{sw}(t) = \frac{4\pi}{3}\rho_{IFM}(t)R_f^3(t) = M_0\left(\frac{t}{t+t_c}\right)^3, \tag{15}$$

and $M_{sw}(t)$ tends to M_0 at $t \gg t_c$ or at $r \gg R_c$. For $\eta \gg 1$ the equality $M_{sw}(t) = M_0/\eta$ gives the relativistic deceleration radius, $R_\gamma = R_c\eta^{-1/3} \ll R_c$. Beyond the relativistic deceleration radius, $r > R_\gamma$, most of the fireball energy is transferred to the sweeping IFM. So the fireball is decelerated as $\Gamma \propto R^{-3/2}$ up to the radius R_c, where the fireball sweeps nearly all mass M_0 of the preceding one. The final Lorentz factor of a fireball in the region $R_c \ll r \ll l_S$ is nearly constant, $\Gamma_c = \Gamma(R_c) = \sqrt{\eta}$. This is because it expands here nearly ballistically and sweeping up only a tiny additional mass from the IFM, as can be seen from Eq. (15). In the case $R_c \geq l_S$ we obtain the same value of the final Lorentz factor of a fireball, $\Gamma_c = \sqrt{\eta}$. This is the final Lorentz factor of a fireball when it hits the boundary of the cavern.

Each fireball (i) sweeps the external gas out to the boundary of the cavern at $r = l_S$; (ii) hits the boundary with a Lorentz factor $\Gamma_c = \sqrt{\eta} \gg 1$ and (iii) leaves inside the cavern its own mass $M_0 = E_0/\eta c^2$. By using Eqs. (10) and (11) for the fireball mass M_0 and cavern radius l_S we find a mean mass density inside the cavern

$$\rho_c = \frac{3}{4\pi}\frac{M_0}{l^3} = \rho_{env}\eta^{-1}, \tag{16}$$

where ρ_{env} is the envelope density. As a result the repeating ultrarelativistic fireballs produce and dynamically support the rarefied cavern inside the massive envelope with a large density contrast $\rho_c/\rho_{env} = \eta^{-1} \ll 1$ between the cavern and envelope. The term 'rarefied' in our case means that the interior mass of the cavern M_0 is connected with the fireball energy by Eq. (10). So the fireball can propagate throughout the cavern relativistically with $\Gamma \gg 1$. There is a convenient relation $R \ll l_S \ll R_{env}$ for the cavern radius l_S under the natural values for the radius of the massive envelope R_{env} from Eq. (4) and radius of near collapsing central NS cluster R from Eq. (7).

3 High Energy Particles in Cavern

The dynamically supported cavern inside the massive envelope is an effective site for production of large fluxes of accelerated particles, because (i) it contains very powerful central source and (ii) it provides the suitable medium for particle acceleration because cavern is filled by expanding fireballs and numerous forwarding and reversing shocks.

3.1 Shocks in Cavern and Envelope

All fireballs hit the cavern boundary at radius $r = l_S$ with a nearly constant Lorentz factor $\Gamma \sim \sqrt{\eta}$. By hitting the envelope fireballs accelerate it. For the lifetime of the hidden source, $t_s \sim 10\ yr$, the envelope is accelerated to a very low velocity

$$v_{env} \sim \frac{\dot{N}_c E_0}{M_{env} c} t_s \sim 10^{-6} M_8^{-1} c, \tag{17}$$

where $\dot{N}_c$ is the NS collision rate, E_0 is the total energy of a fireball and M_{env} is a mass of the envelope. If to consider the envelope as quasistationary and the fireballs as continuous flow (due to repeating hitting) of relativistic gas hitting the wall, one concludes on the existence of the dynamically supported (quasi)standing shock at the boundary of the cavern and envelope. This is in contrast to the standard GRB model when expanding single fireball with the instant radius R_f gradually diminishes its Lorentz factor, $\Gamma \propto R_f^{-3/2}$, by expanding through the homogeneous ISM and does not produce any standing shock by reaching the Sedov length l_S. In our case the preceding fireballs create and support the rarefied cavern at radius $r = l_S$ in the dense medium. Accordingly the forthcoming fireballs propagates through this cavern relativistically and produce the standing shock by hitting the cavern boundary with the Lorentz factor $\Gamma \sim \sqrt{\eta}$..

A mean total number of fireballs existing at the same time in the cavern is $N_f = l_S/R_c \gg 1$, where the distance between successive fireballs is determined by Eq. (12). Numerous internal shocks in these fireballs produce highly inhomogeneous IFM with relativistic relative movement of separate gas components. Shocks generated by repeating fireballs are ultrarelativistic inside the cavern and mildly relativistic near the standing shock at the cavern boundary. The multiple forward and reversed shocks in the cavern would provide the strong turbulization of the internal gas.

In summary, different types of shocks exist simultaneously inside the cavern: (i) the numerous external and internal ultrarelativistic shocks from N_f expanding fireballs; (ii) the quasistationary standing shock at the cavern boundary and (iii) the $\sim N_f$ inward moving reverse shocks generated after each fireball hitting of the cavern boundary. It is expected that these shocks produce well developed mildly relativistic turbulent medium favorable for generation of magnetic field and particle acceleration.

3.2 Magnetic Field Equipartition

The turbulent plasma created by the numerous shocks from repeated fireballs is a suitable place for the generation of magnetic field by the dynamo mechanism. The mean value of magnetic field H on the scale of the cavern size l_S can be estimated from the equipartition relation between the energy density of turbulent motion and dynamo-induced magnetic field:

$$\frac{H^2}{8\pi} = f_{eq}\frac{\rho_c u_t^2}{2}, \tag{18}$$

where ρ_c is the gas density inside the cavern, u_t is a characteristic velocity of turbulent motions in the gas, and $f_{eq} \sim 1$ can be assumed. Ultrarelativistic shocks produce mildly relativistic turbulent motions inside the cavern and near the standing shock, so $u_t \simeq c$. With equipartition relation 18 and using Eqs. (16) and (18), one obtains the following value for the equipartition magnetic field inside the cavern:

$$H = (4\pi f_{eq}\rho_{env}c^2/\eta)^{1/2} \simeq 1.4 \cdot 10^2 f_{eq}^{1/2}\eta_3^{-1/2}n_9^{1/2}\ \mathrm{G}, \tag{19}$$

where $n_{env} = 10^9 n_9$ cm^{-3} is the envelope gas number density from Eq. (5) and $\eta = 10^3\eta_3$ (see Eq. (10)) is the baryon-loading mass parameter of the fireball .

3.3 Particle Acceleration

Two acceleration mechanisms, Fermi II and Γ^2, operate in the cavern. Cavern is filled by multiple colliding shocks like in case of GRBs [28]. This results in the turbulization of the medium with the shock spectrum of turbulence, $F_k \sim k^{-2}$, where k is a wave number. Assuming equipartition magnetic field on each scale $l{\sim}1/k$, $\quad H_l^2 \sim kF_k$, one obtains the distribution of magnetic fields over the scales as

$$H_l/H_0 = (l/l_0)^{1/2}, \tag{20}$$

where l_0 is a maximum scale with the coherent field H_0 there. One can take the Sedov length l_S as l_0 and H_0 as given by Eq. (19). The maximum energy of accelerated particles is given by

$$E_{max} = ZeH_0 l_0 \simeq 4.9 \cdot 10^{19} Z E_{52}^{1/3} \eta_3^{-1/2} f_{eq}^{1/2} n_9^{1/6} \text{ eV}, \tag{21}$$

and acceleration time up to $E \sim E_0$

$$t_{ac} \sim \frac{l_0}{c} \left(\frac{v}{c}\right)^2 \sim 4.0 \cdot 10^4 E_{52}^{1/3} n_9^{-1/3} \text{ s}, \tag{22}$$

where mildly relativistic turbulence $v \sim c$ is assumed. The typical time of energy losses, determined by pp-collisions, is much longer:

$$t_{pp} = \left(\frac{1}{E}\frac{dE}{dt}\right)^{-1} = \frac{1}{f_p \sigma_{pp} n_c c} \simeq 1.1 \cdot 10^9 \eta_3 n_9^{-1} \text{ s}, \tag{23}$$

where $f_p \approx 0.5$ is the fraction of energy lost by HE proton in one collision, σ_{pp} is a cross-section of pp-interaction, and n_c is the gas number density in the cavern. The particles accelerated by Fermi II mechanism are reaccelerated by relativistically moving fireballs. A particle with energy E_i, when reflected from a fireball with Lorentz factor Γ can obtain maximum energy $E_{max} = 2\Gamma^2 E_i$. This Γ^2- mechanism of acceleration works only in prehydrodynamical regime of fireball expansion, after reaching the hydrodynamical stage, Γ^2 mechanisms ceases [29].

4 Neutrino Production and Detection

Particles accelerated in the cavern interact with the gas in the envelope producing high energy neutrino flux. We assume that about $10 - 30\%$ of the total power of the source L_{tot} is converted into energy of accelerated particles $L_p = \xi L_{tot} \sim (1-3)10^{47}$ erg/s. As estimated in Section 2.1, the column density of the envelope varies from $X_{env} \sim 10^2$ g/cm^2 up to $X_{env} \sim 10^4$ g/cm^2. Taking into account the magnetic field, one concludes that accelerated protons loose in the envelope a substantial fraction of their energy. The charged pions, produced in pp-collisions, with Lorentz factors up to $\Gamma_c \sim 1/(\sigma_{\pi N} n_{env} c \tau_\pi) \sim 4 \cdot 10^{13} n_9^{-1}$ freely decay in the envelope (here $\sigma_{\pi N} \sim 3 \cdot 10^{-26}$ cm^2 is πN-cross-section, τ_π is the lifetime of charged pion, and $n_{env} = 10^9 n_9$ cm^{-3} is the number density of gas in the envelope). We assume E^{-2} spectrum of accelerated protons

$$Q_p(E) = \frac{L_p}{\eta E^2}, \tag{24}$$

where $\eta = \ln(E_{max}/E_{min}) \sim 20-30$. About half of its energy protons transfer to high energy neutrinos through decays of pions, $L_\nu \sim (2/3)(3/4)L_p$, and thus the production rate of $\nu_\mu + \bar{\nu}_\mu$ neutrinos is

$$Q_{\nu_\mu+\bar{\nu}_\mu}(> E) = \frac{L_p}{4\eta E^2} \tag{25}$$

Crossing the Earth, these neutrinos create deep underground the equilibrium flux of muons, which can be calculated as [30]:

$$F_\mu(> E) = \frac{\sigma_0 N_A}{b_\mu} Y_\mu(E_\mu) \frac{L_p}{4\xi E_\mu} \frac{1}{4\pi r^2}, \tag{26}$$

where the normalization cross-section $\sigma_0 = 1 \cdot 10^{-34}$ cm^2, $N_A = 6 \cdot 10^{23}$ is the Avogadro number, $b_\mu = 4 \cdot 10^{-6}$ cm^2/g is the rate of muon energy losses, $Y_\mu(E)$ is the integral muon moment of $\nu_\mu N$ interaction (see e. g. [2, 30]). The most effective energy of muon detection is $E_\mu \geq 1$ TeV [30]. The rate of muon events in the underground detector with effective area S at distance r from the source is given by

$$\dot{N}(\nu_\mu) = F_\mu S \simeq 70 \left(\frac{L_p}{10^{48}\ \mathrm{erg\ s^{-1}}}\right) \left(\frac{S}{1\ \mathrm{km}^2}\right) \left(\frac{r}{10^3\ \mathrm{Mpc}}\right)^{-2} \quad \mathrm{yr}^{-1}. \tag{27}$$

Thus, we expect about 10 muons per year from the source at distance 10^3 Mpc.

5 Accompanying Radiations

We shall consider below HE gamma-ray radiation produced by accelerated particles and thermalized infrared radiation from the envelope. As far as HE gamma-ray radiation is concerned, there will be considered two cases: (i) thin envelope with $X_{env} \sim 10^2$ g/cm^2 and (ii) thick envelope with $X_{env} \sim 10^4$ g/cm^2. In the latter case HE gamma-ray radiation with $E_\gamma > 1$ MeV is absorbed.

5.1 Gamma-Ray Radiation

Apart from high energy neutrinos, the discussed source can emit HE gamma radiation through $\pi^0 \to 2\gamma$ decays and synchrotron radiation of of the electrons. In case of the thick envelope with $X_{env} \sim 10^4$ g/cm^2 most of HE photons are absorbed in the envelope (characteristic length of absorption is the radiation length $X_{rad} \approx 60$ g/cm^2). Only photons with $E_\gamma \leq m_e c^2 \sim 1$ MeV escape. In the case of the thin envelope, $X_{env} \sim 100$ g/cm^2, HE gamma radiation emerges from the source. Production rate of the synchrotron photons can be readily calculated as

$$dQ_{syn} = \frac{dE_e}{E_\gamma} Q_e(> E_e), \tag{28}$$

where E_e and E_γ are the energies of electron and of emitted photon, respectively. Using $Q_e(> E_e) = L_e/(\eta E_e)$ and $E_\gamma = k_{syn}(H)E_e^2$, where k_{syn} is the coefficient of the synchrotron production, one obtains

$$Q_{syn}(E_\gamma) = \frac{1}{12}\frac{L_p}{\eta E_\gamma^2}. \tag{29}$$

Note, that the production rate given by Eq.(29) does not depend on magnetic field. Adding the contribution from $\pi^0 \to 2\gamma$ decays, one obtains

$$Q_\gamma(E_\gamma) = \frac{5}{12}\frac{L_p}{\eta E_\gamma^2}, \tag{30}$$

and the flux at $E_\gamma \geq 1$ GeV at the distance to the source $r = 1 \cdot 10^3$ Mpc is

$$\begin{aligned} F_\gamma(> E_\gamma) &= \frac{5}{12}\left(\frac{1}{4\pi r^2}\right)\frac{L_p}{\xi E_\gamma} \\ &\simeq 2.2 \cdot 10^{-8} \left(\frac{L_p}{10^{47}\ \text{erg s}^{-1}}\right)\left(\frac{r}{10^3\ \text{Mpc}}\right)^{-2}\ \text{cm}^{-2}\ \text{s}^{-1}, \end{aligned} \tag{31}$$

i. e. the source is detectable by EGRET.

5.2 Infrared and Optical Radiations

Hitting the envelope, fireballs dissipate part of its kinetic energy in the envelope in the form of low-energy e-m radiation. This radiation is thermalized in the optically thick envelope and then re-emitted in the form of black-body radiation from the surface of the envelope. The black-body luminosity can be estimated as

$$L_{bb} = \xi_b \dot{N}_c E_0 \simeq 1.4 \cdot 10^{48} \xi_b E_{52}(v/0.1c)^{31/7} N_6^{-1} \xi_b\ \text{erg s}^{-1}, \tag{32}$$

where E_0 is a total energy of a fireball, $\dot{N}_c$ is the NS collision rate in the cluster given by Eq. (8), and ξ_b is a fraction of the total fireball energy dissipated in the form of low-energy e-m radiation. The temperature of black-body radiation corresponds to the infrared radiation:

$$T_{bb} = \left(\frac{L_{bb}}{4\pi R_{env}^2 \sigma_{SB}} \right)^{1/4} \simeq 5.1 \cdot 10^3 \xi_b^{1/4} E_{52}^{1/4} v_{0.1}^{31/28} N_6^{-1/4} M_8^{-1/2} \text{ K}, \tag{33}$$

The luminosity L_{bb} exceeds the Eddington luminosity of the whole NS cluster $L_E = 4\pi G N m m_p c/\sigma_T$, if

$$v > v_E = \left(\frac{\pi}{18\sqrt{2}} N^2 \frac{m_p c^2}{E_0} \frac{r_g^2}{\sigma_T} \right)^{7/31} c \simeq 1.2 \cdot 10^{-2} E_{52}^{-7/31} N_6^{14/31} c. \tag{34}$$

However, this radiation appears long time after HE neutrino and gamma radiations. The thermalized radiation diffuses through the envelope with the diffusion coefficient $D \sim c l_{dif}$, where the diffusion length is $l_{dif} = 1/(\sigma_T n_{env})$ and σ_T is the Thompson cross-section. The time of the radiation diffusion through the envelope of radius R_{env} is

$$t_d \sim \frac{R_{env}^2}{D} \sim 1 \cdot 10^4 \; yr, \tag{35}$$

independently of the envelope mass. This diffusion time is to be compared with the duration of the active phase $t_s \sim 10$ years and with the time of flight $R_{env}/c \sim 2$ years. We conclude thus that IR luminosity of the envelope during the neutrino burst is the same as during secular evolution (disruption of the normal stars). The non-thermal optical radiation can be produced due to HE proton-induced pion decays in the outer part of the envelope, but its luminosity is very small.

5.3 Duration of activity and the number of sources

As was indicated in Section 2.2 the duration of the active phase t_s is determined by relaxation time of the NS cluster: $t_s \sim t_{rel} \sim 10 - 20$ yr. This stage appears only once during the lifetime of a galaxy, prior to the MBH formation. If to assume that a galactic nucleus turns after it into AGN, the total number of hidden sources in the Universe can be estimated as

$$N_{HS} \sim \frac{4}{3}\pi (3ct_0)^3 n_{AGN} t_s / t_{AGN}, \tag{36}$$

where $\frac{4}{3}\pi(3ct_0)^3$ is the cosmological volume inside the horizon ct_0, n_{AGN} is the number density of AGNs and t_{AGN} is the AGN lifetime. The value t_s/t_{AGN} gives a probability for AGN to be observed at the stage of the hidden source, if to include this short stage ($t_s \sim 10\ yr$) in the much longer (t_{AGN}) AGN stage and consider (for the aim of estimate) the hidden source stage as the accidental one in the AGN history. The estimates for n_{AGN} and t_{AGN} taken for different populations of AGNs result in $N_{HS} \sim 10 - 100$.

6 Conclusions

Dynamical evolution of the central stellar cluster in the galactic nucleus results in the stellar destruction of the constituent normal stars and in the production of massive gas envelope. The surviving subsystem of neutron stars (NS) sinks deep inside this envelope. The fast repeating fireballs caused by NS collisions in the central stellar cluster create the rarefied cavern inside the massive envelope. Colliding fireballs and shocks produce the turbulence in the cavern, and particles are accelerated by Fermi II mechanism. These particles are then reaccelerated by Γ^2-mechanism in collisions with relativistic shocks and fireballs.

All high energy particles, except neutrinos, can be completely absorbed in the thick envelope. In this case the considered source is an example of a powerful hidden source of HE neutrinos. In contrast to HE neutrino generation in AGN, the discussed source is characterized by negligible rate of $p\gamma$ energy losses of accelerated protons. This is due to much larger size of acceleration site: while the size of cavern is of order of the Sedov length $l_S \sim 1$ pc, the size of of acceleration region in AGN is of order of gravitational radius of the central MBH, $R_g \sim 10^{-5}$ pc. The other advantages of our model are very efficient acceleration of the particles in the cavern and large luminosity of the source $L_{tot} \gg L_{Edd}$. Additionally to HE neutrinos, observational signatures of the considered sources are given by recurrent GRBs (in cases when they are not obscured) and by gravitational radiation.

Prediction of high energy gamma-ray flux depends on the thickness of envelope. In case of the thick envelope, $X_{rad} \sim 10^4$ g/cm^2, HE gamma radiation is absorbed, and only low energy gamma-rays with $E_\gamma < 1$ MeV can be observed. When an envelope is thin, $X_{rad} \sim 10^2$ g/cm^2, gamma-ray radiation from $\pi^0 \to 2\gamma$ decays and from synchrotron radiation of the secondary electrons can be observed by EGRET and marginally by Wipple detector at $E_\gamma \geq 1$ TeV. The source is to be seen as bright IR source but, due to slow diffusion through envelope, this radiation appears after $\sim 10^4$ years after the phase of neutrino activity. During the period of neutrino activity the IR luminosity is the same as before it.

The expected duration of neutrino activity for a hidden source is ~ 10 yr, and the total number of hidden sources in the horizon volume ranges from a few up to ~ 100, within uncertainties of the estimates.

Underground neutrino detector with an effective area $S \sim 1$ km^2 will observe ~ 10 muons per year with energies $E_\mu \geq 1$ TeV from this hidden source.

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